X-band ISAR imagery of scale-model tactical targets using a wide bandwidth 350GHz compact range.

Thomas M. Goyette[*] [a], Jason C. Dickinson [a], William J. Gorveatt [a], Jerry Waldman[a], William E. Nixon [b]

[a]Submillimeter-Wave Technology Laboratory, University of Massachusetts Lowell, 175 Cabot St., Lowell, MA 01854

[b]U.S. Army National Ground Intelligence Center, 2055 Boulders Road, Charlottesville, VA 22911

ABSTRACT

The demand for high-resolution ISAR data on tactical targets at all radar bands has been growing steadily. Here we describe a new 350GHz compact range currently being constructed to acquire fully polarimetric X-band data using 1/35th scale models. ERADS currently operates compact ranges from X to W-band using 1/16th scale models. The addition of this new compact range using 1/35th scale models will permit the measurement of larger targets and the measurement of multiple targets arranged in a scene. It will also allow us to take advantage of the large number of commercially available models at 1/35th scale. The 350GHz transceiver uses two high-stability optically pumped far-infrared lasers, microwave/laser 350GHz mixer side-band generation for frequency sweep, and a pair of waveguide mounted diode receivers for coherent integration. The 35GHz bandwidth at a center frequency of 350GHz will allow the X-band transceiver system to collect data with up to 6-inch down range resolution, with a round trip half power beam diameter corresponding to 60 feet. Tactical targets may be measured in free space or on various ground planes, which simulate different types of terrain. Compact range measurements of simple calibration objects have been performed and compared to theoretical results using computer code predictions. A correlation study of X-band data using field measurements, 1/35th scale models and 1/16th scale models is planned upon completion of compact range construction. Available results of the diagnostic tests and the correlation study will be presented.

Keywords: Sub-millimeter wavelength, Radar, Imagery, Modeling.

1. INTRODUCTION

As radar systems continue to advance in their capabilities there is a steadily increasing need for high quality radar cross-section (RCS) and target signature data. These data have become essential for successful development of enhanced capabilities such as automatic target recognition (ATR). For this reason the U. S. Army National Ground Intelligence Center (NGIC) Expert Radar Signature Solutions (ERADS) program including the Submillimeter-Wave Technology Laboratory (STL) at U Mass Lowell has developed state-of-the-art compact radar ranges to measure the radar return of scale models of targets of interest. Over the past 20 years compact ranges have been developed to model VHF/UHF, X-band, Ka-band, and W-band radar systems. Target signature data are collected by measuring scale models at proportionally scaled wavelengths. Since X-band (10GHz) is a radar frequency that is of particular interest we have developed a new compact range to measure additional X-band target signature data. This new compact range has a wide bandwidth and full polarimetric capabilities.

The mathematics and theory of using scale models and proportionally scaled wavelengths to study the scattering of electromagnetic radiation has been well known since the late 1940's.[1] Much more recently studies have shown that data taken on a high quality 1/16th scale model compares very well with the same data taken on the full-scale target.[2] Heretofore the compact radar ranges developed under the ERADS program have performed the vast majority of measurements using 1/16th scale models. However, the recently developed VHF/UHF compact range at STL has been designed to use 1/35th scale models in order to conveniently match the operating range of existing equipment.[3] It is useful

[*] Correspondence: Email: Thomas_Goyette@uml.edu; Telephone: (978) 458-3807; Fax: (978) 452-3333.

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to note that 1/35th scale models, which are readily available through commercial sources, needed only some straightforward modifications in detail and dielectric materials in order for them to accurately simulate the full-scale target. While it is a straightforward process, an expert model builder with detailed knowledge of the target is needed to meticulously apply these modifications. In addition to the wide variety of target models at 1/35th scale, the smaller physical size of the models allows much larger vehicles to be measured than had been previously possible. For example, a beam diameter of 30" corresponds to a target 40 feet in length at 1/16th scale or a target 87-feet in length at 35th scale. Because of these advantages it was decided to develop a new compact range operating at 350 GHz to simulate X-band measurements using 1/35th scale models. Since the ERADS program currently operates a number of high quality compact ranges to collect X-band data on 1/16th scale models, the 350GHz compact range will provide additional data collection opportunities. Once completed, X-band measurements would be made on the 1/35th scale model and compared with measurements made on the 1/16th scale model from a compact range operating at 160GHz, as well as field data. Preliminary results of measurements in the 350GHz compact range have been taken and will be presented. These results include beam width and beam phase measurements, measurements of simple calibration objects and the comparison of these results to theoretical predictions, and radar images taken on the 1/35th scale models.

2. THE 350GHz COMPACT RADAR RANGE

A laser based compact radar range designed to model W-band radar has been described previously.[4] The newly constructed 350GHz compact range is very similar in general layout and is shown in a simplified view in Figure 1. In order to model X-band using a 1/35th scale model two very-high-stability far infrared (FIR) lasers were developed as the base transmit and receive sources. The lasers consist of two ultra-stable, 150 W, grating-tunable CO_2 lasers that are used as the optical pumps for the two FIR lasers. The CO_2 lasers are set to produce 10μm wavelength radiation (10R14 and 10R32 laser transitions, respectively). The outputs of the lasers are used to excite the molecular gas transitions in deuterated Formic acid (HCOOD). The formic acid FIR lasers then produce frequencies of 323.6770GHz and 325.8842GHz, respectively.

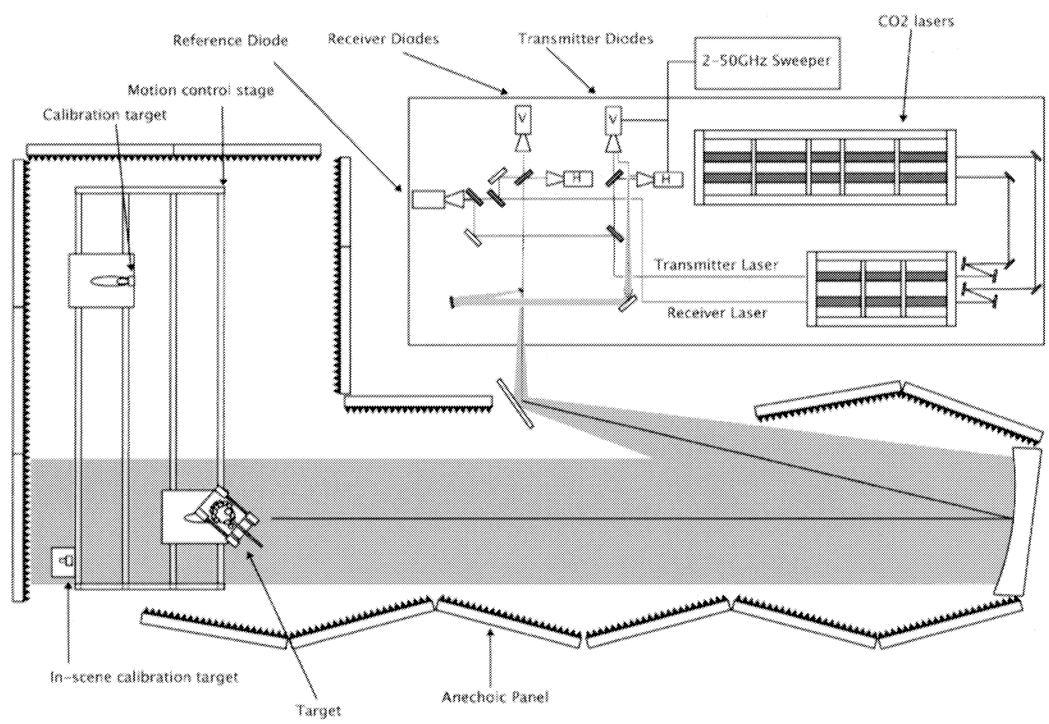

Figure 1. Diagram of the 350GHz compact radar range.

The zero order Gaussian modes produced by the FIR lasers emerge with a width of 19mm full width at half maximum (FWHM). Typically, 50mW of power is measured at the laser output. One laser is used as the local oscillator for the receiver diodes. The receiver diodes shown in Figure 1 consist of a new, high-efficiency, ultra-wide-bandwidth diode mounted in a fundamental waveguide.[a] A high gain diagonal horn that produces a very good beam pattern is used as a transition from waveguide to free space. The local oscillator (LO) laser beam is propagated quasi-optically to illuminate the receiver diode. The field-of-view of the receiver diode is set by a combination of focusing mirrors and lenses such that it will achieve an overlap with the transmitter. The transmitter diodes shown in Figure 1 consist of diodes that are very similar in mechanical design to the receiver diodes. Identical high-gain diagonal horns are also used to form the transition from fundamental waveguide to free space for the transmitter diodes. The output of the transmitter laser is propagated to the transmitter diodes and illuminates them through a specially designed silicon etalon. The transmitter diodes then mix the incident laser power with an externally applied variable frequency signal from the 2-50GHz microwave sweeper seen in Figure 1. The transmitter diodes are optimized to efficiently radiate the resulting sideband power. The silicon etalons, which are designed for 99% transmission of the laser frequency, reflect the sideband frequency with very high efficiency. This allows the frequency tunable sideband to be separated from the unshifted laser frequency. The transmitter sideband is then collimated using the 45-inch diameter 250-inch focal length mirror that is used as the primary antenna for illuminating the target. Backscattered electromagnetic radiation is collected by the primary antenna and propagated into the receiver.

350GHz Compact Range	**(Full Scale)**
350 GHz Center Frequency	(10 GHz Full scale)
35 GHz Bandwidth	(1 GHz Full Scale)
0.169" Range Resolution	(5.92" Full Scale)
20" Two Way Beam Width (-3dB)	(58.3' Full Scale)
Far Field Beam, 0.3° bistatic	
Fully Polarimetric HH, HV, VH, VV amplitude and phase	

Table 1. Radar parameters for the 350GHz compact range when modeling X-Band.

The target shown in Figure 1 can be mounted either on a low cross-section pylon to provide free space measurements, or on a dielectric ground plane to simulate various environments such as desert, wet or dry soil, asphalt, etc. The pylon is set in the middle of a chamber whose walls are covered with a specially designed material (FIRAM®) that is highly absorbing at 350GHz. This setup is done to minimize the amount of backscattered radiation from objects other than the target. The tunable microwave source is swept in order to produce a frequency chirp centered at 350GHz with a 35 GHz bandwidth. This accurately models 10GHz at 1/35th scale with a scaled bandwidth of 1GHz. While this bandwidth provides a range resolution of 0.169 inch at 350GHz, it corresponds to a range resolution of 5.92 inch on the (full-scale) X-band target. The compact range is designed to transmit and receive both horizontal and vertical polarization providing the full polarimetric scattering matrix information. Since the transmitter diodes produce both the upper and lower sideband frequencies, specially designed metal mesh frequency filters are used to separate the upper sideband from the lower sideband, which is centered at 300GHz. Either sideband can be used depending on the requirements of the measurement. However, the upper sideband is used for simulation of X-band. The general operating parameters of the compact range are listed in Table 1 and will be discussed further in Section 3.

In addition to operating the system in a range-gated ISAR mode as described above, it is also possible to bypass the transmitter diodes and send the transmitter laser beam out to illuminate the target directly. While this technique provides no range information, images can be formed in the azimuth and elevation (Az/El) cross range directions to provide two-dimensional images. The data is collected by simply viewing the target in a controlled fashion through a solid angle in both the azimuth and elevation directions and recording the amplitude and phase at each point. Two Fourier transforms (one in each direction) are all that is required to produce an image from this data. This technique has proven very useful for both initial system diagnostics and also in identification of individual scattering centers on the target. The results, which include examples of this single frequency Az/El imaging, will be presented.

[a] Diode type VDI-WR2.8-FM-S00012 From Virginia Diodes Inc. 321 West Main Street Charlottesville, VA 22903.

3. RESULTS

3.1. Compact range diagnostic measurements.

Diagnostic measurements using simple test objects have proven very useful in determining the compact range operational parameters, some of which are listed in Table 1. Measurements of the two way field of view (beam power halfwidth) and phase taper of the compact range are very important in ensuring the quality of the radar data collected. In this section we present the results of the measurements that are used to verify the operational accuracy of the new compact range.

Figure 2 shows the results of the direct measure of the sideband power emitted from the transmitter diode in Figure 1. For these measurements the output of the transmitter diode was swept across the 331GHz to 366GHz frequency range by varying the output of the microwave sweeper from 5GHz to 40GHz. The transmitted sideband was then focused into a power meter.[b] The measured power, ignoring coupling losses, is plotted in Figure 2. The power level is approximately an order of magnitude greater than that available from previous sideband generator diodes. It can be seen that the power generated by the sideband generator has fluctuations of several dB across the entire bandwidth.

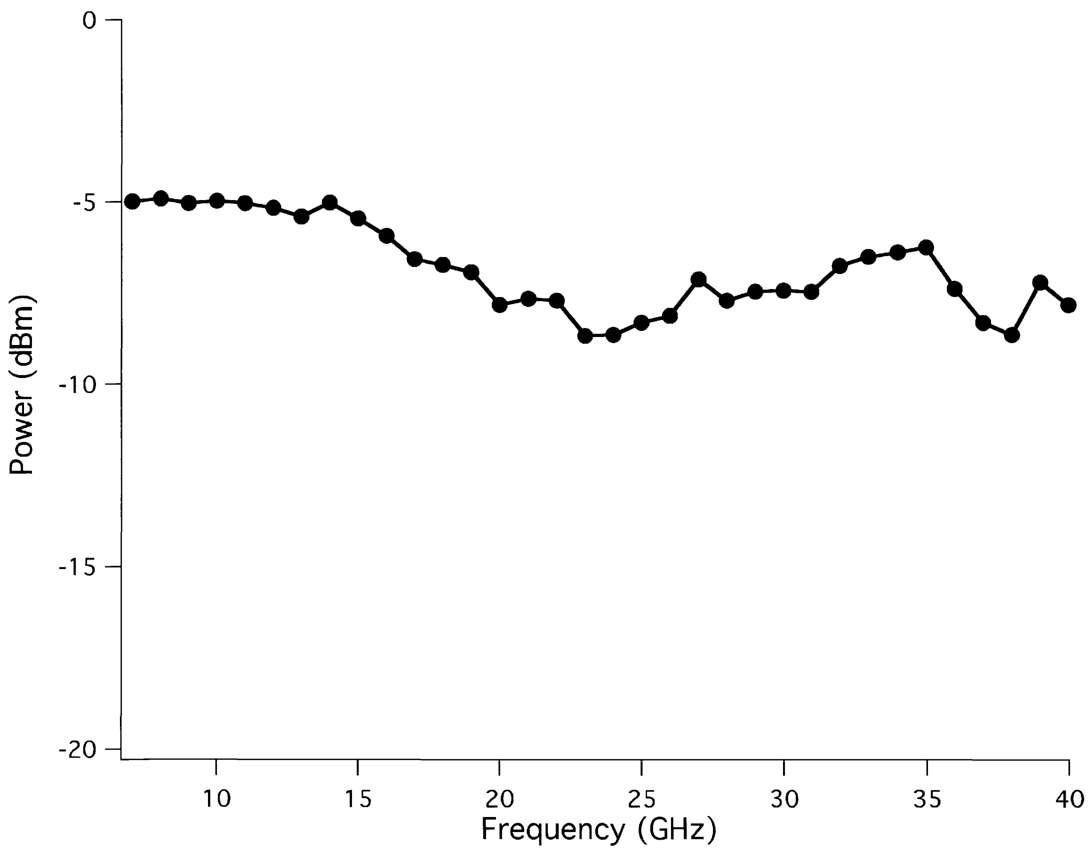

Figure 2. Measured sideband power as a function of sweeper frequency.

These reproducible fluctuations are calibrated out during data collection. The bandwidth of the transmitter diode is in fact somewhat wider, with similar power being measured at sweeper frequencies of up to 50GHz. However, due to the bandwidth limit of several amplifiers, the compact range will initially operate only up to a sweeper frequency of 40GHz.

[b] Power meter model PM2 made by Erickson Instruments LLC, 316 Pine Street Amherst MA 01002.

The results of a two-way field-of-view measurement are shown in Figure 3. The data in Figure 3 was collected by aligning the field-of-view of the receiver diode to coincide with the outwardly propagating transmitter laser. In these measurements the sideband generator diodes were bypassed and the output of the transmitter laser was sent to illuminate the target directly. This technique allowed the receiver field of view to be established more easily for the initial setup since it did not require the more complex electronics of the sideband generator. A small flat plate (0.5"x0.5") was then scanned across the target zone. It can be seen from Figure 3 that the 2-way beam has a half power diameter of 20". This will allow a model corresponding to a target of 58' to be scanned within the 3dB power points. Currently, diagnostics on the radiation emitted from the sideband generator are being completed. Upon completion, the sideband power will be propagated along the same path as the transmit laser and the 2-way field of view will be re-measured.

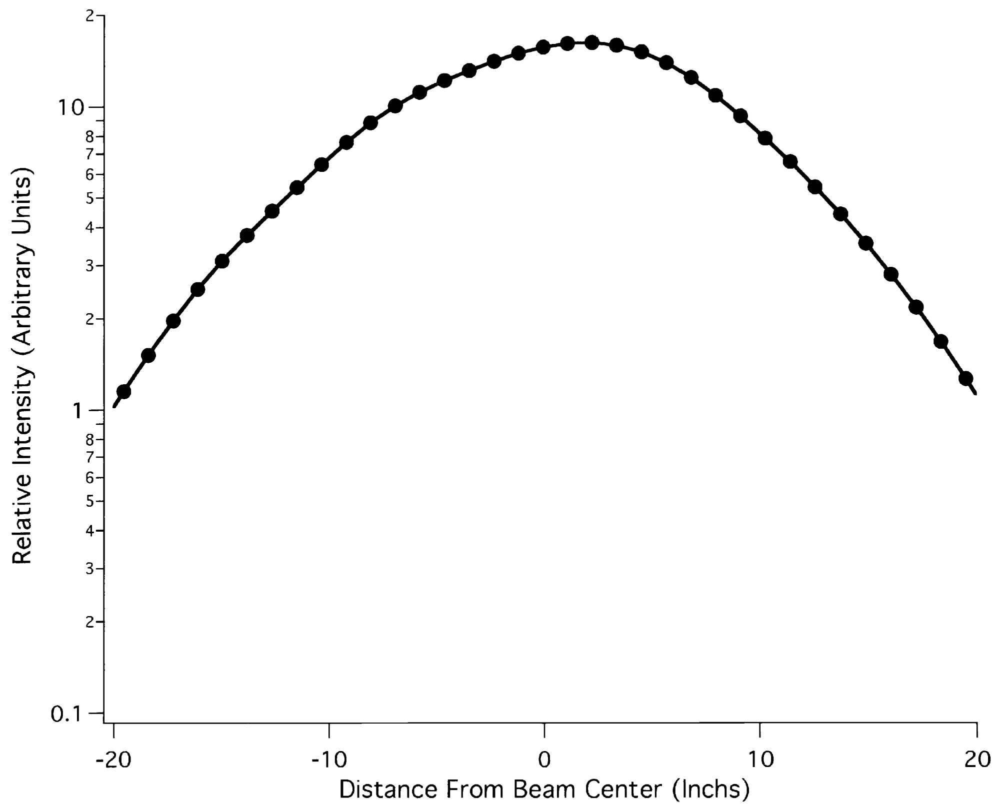

Figure 3. Two-way field of view measurement across the target zone in the compact range.

The phase across the target zone has also been measured in a similar fashion. These results are shown in Figure 4. In this measurement the phase of a flat plate was recorded as it was moved across the region where the target would normally be mounted in the compact range. Since there is always a slight angle between the orientations of the scanning stage relative to the transmitted radar beam, the flat mirror does exhibit a small motion forward as it is scanned from one side to the other. This movement results in a measurable linear change in phase as the scan is performed. However, the recorded phase of the test object can be fit to a straight line to remove the linear part of the phase change. The result is the direct measure of the phase across the compact range in the region of the target. The graph in Figure 4 shows that the variation of the phase of the radar beam across the 20" FWHM beam diameter is typically less than 10 degrees. This result is consistent with a high-quality far-field radar system. It is also possible to produce any desired phase front by simply changing the optical configuration of the range. This flexibility allows us to simulate a wide variety of near-field radar systems as well. It is believed that the residual fluctuations in phase seen in Figure 4 are in fact due to a slight mechanical deflection of the scanning stage that holds the flat plate as it is translated across the radar beam. This type of motion can be compensated for by the use of a laser interferometer to monitor the position of the scanning stage.

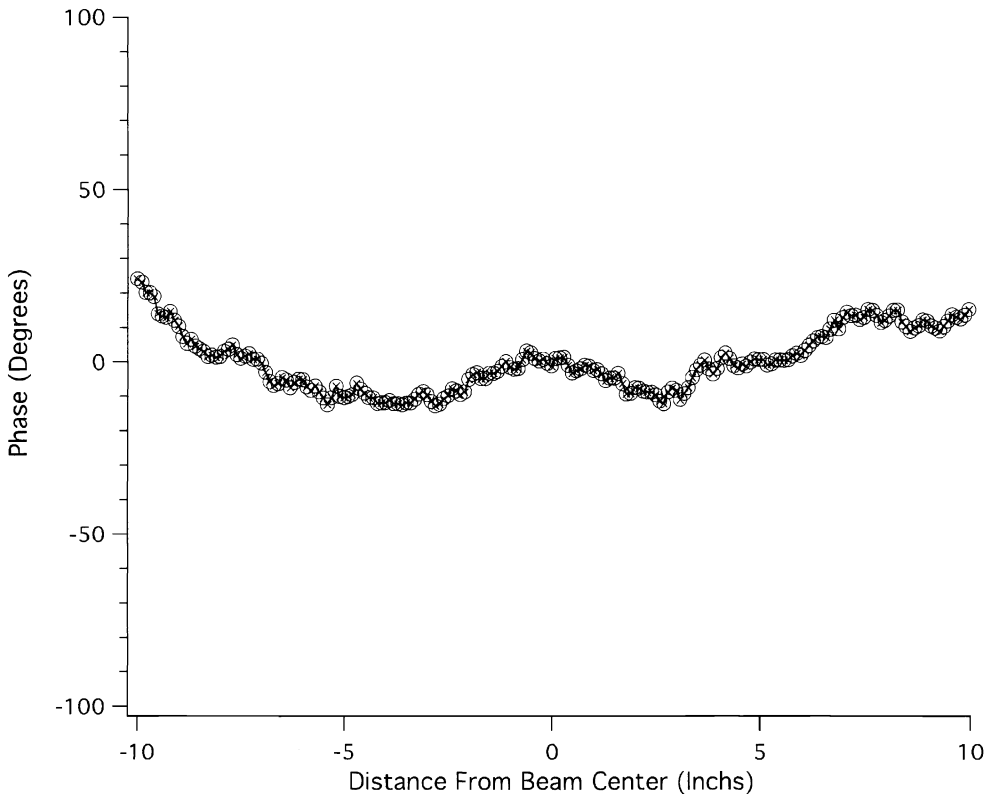

Figure 4. Phase measurement across the radar target zone.

3.2. Comparison of simple objects to theory.

For demonstrating compact range performance, it is essential to compare results of measurements made on simple calibration objects to the predictions from standard theoretical calculations. Radar cross-section measurements made on basic geometric objects allow us to test not only the entire down-converting electronics of the new compact range but also the motion control, object orientation and linearity of signal levels over a wide dynamic range. Figures 5 and 6 show graphs of the measured RCS of a 1-inch cube measured at different elevation angles. These graphs are plotted in dBsm at X-band where this cube is equivalent to a 38.8dBsm object due to the 1/35th scale factor. Also plotted in these figures are the predicted RCS, calculated using the Geometric Theory of Diffraction (GTD). In Figure 5 the cube was adjusted to 0 degrees elevation such that its specular reflection was fully captured by the primary antenna. There is excellent agreement between the measured RCS (dashed line) and the predicted RCS (solid line) from the GTD codes. A close examination shows that even the small fluctuations predicted in the 30degree to 40degree region are reproduced with accuracy.

Since at 0 degrees elevation the RCS returned from the cube is relatively large at most azimuth angles, the cube was set to approximately 1.5 degrees in elevation. This angle corresponded to the first side-lobe of the cube in the elevation direction. The cube was then scanned again and compared to the calculated result from GTD. Again, the measured RCS is in excellent agreement with the prediction, as is seen in Figure 6. Figures 5 and 6 show that the compact range is able to accurately measure individual X-band RCS values down to the –20dBsm level. The measurements were made using a 10KHz resolution bandwidth. This bandwidth limited the signal-to-noise of the system since it corresponds to an integration time of 100μs. It is straightforward to improve this signal-to-noise level by longer integration times. For example, a typical data collection sweep takes 1second. This would improve the signal to noise of the data when Fourier transformed by a factor of approximately 40dB. Since the efficiency of the sideband generator introduces an additional loss of approximately 20dB the signal to noise in the range-gated mode will be improved by 20dB in a 1 second sweep. This improvement corresponds to a noise floor of –40dBsm in a 1 second sweep at X-band while that for using the laser frequency directly is –60dBsm.

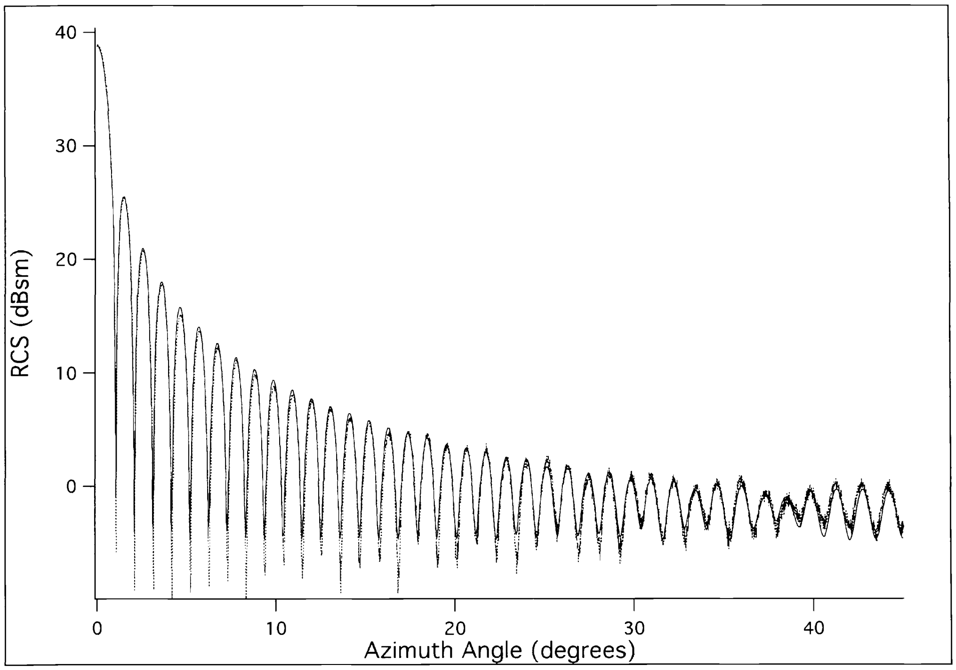

Figure 5. Measured (dashed line) and calculated (solid line) X-band RCS return from cube at 0.0 degrees elevation.

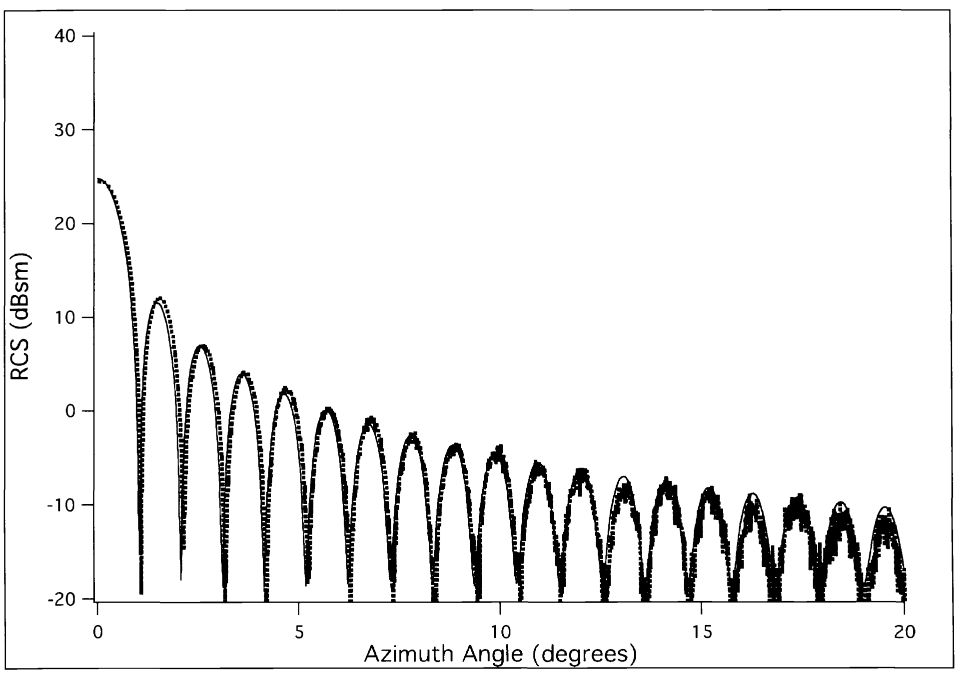

Figure 6. Measured (dashed line) and calculated (solid line) X-band RCS return from a cube at 1.5 degrees elevation.

3.3. X-band imaging of 1/35th scale targets.

Figure 7 shows a 1/35th scale model and a 1/16th scale model of the same T72 tank. The pre-existing 1/16th scale T72 model was used as a design template for the modification of a commercially available 1/35th scale model. The 1/35th scale model was built and modified to provide as close a match as possible to the features of the 1/16th scale model. These models of the same tank will now be used in a study to compare the results of RCS and ISAR images measured at different scale factors, but both modeling X-band frequency. At the time of this publication diagnostic measurements were being completed on the sideband generators. Therefore, it was not possible to include wide bandwidth results in this paper. As can be seen from Figure 7 the visual detail compares very well between the two target models. Since there were no pre-existing commercially available $1/16^{th}$ scale models of the T72, the $1/16^{th}$ scale model seen in Figure 7 was constructed entirely from parts fabricated by the ERADS program. This allows the model builder to reproduce precise details, but it can be time-consuming to prepare models. The commercially available $1/35^{th}$ scale models provide a very reasonable alternative in time, effort and expense of fabrication. ERADS has previously demonstrated that ISAR image data on 1/16-scale models strongly correlates with field data on the same target.[2] If this correlation can be extended to $1/35^{th}$ scale, a considerably larger inventory of model targets will become accessible.

Target imagery was collected using the Az/El imaging technique that was described in Section 2. Single frequency data were recorded in amplitude and phase continuously on several $1/35^{th}$ scale targets from 5° elevation to 15° elevation in 360° aspect with an angular spacing of 0.005° in aspect and 0.02° in elevation. While range cannot be calculated from a single frequency, the two-dimensional images in azimuth cross-range and elevation cross-range can be formed continuously at any arbitrary aspect angle by performing a 2D Fourier transform. This technique is very useful in identifying individual scatterers on a target and also identifying problems with the field-of-view of the system. Images were integrated over a 10° by 10° angular window and have cross-range resolutions of 3.66" at X-band on the full-scale target.

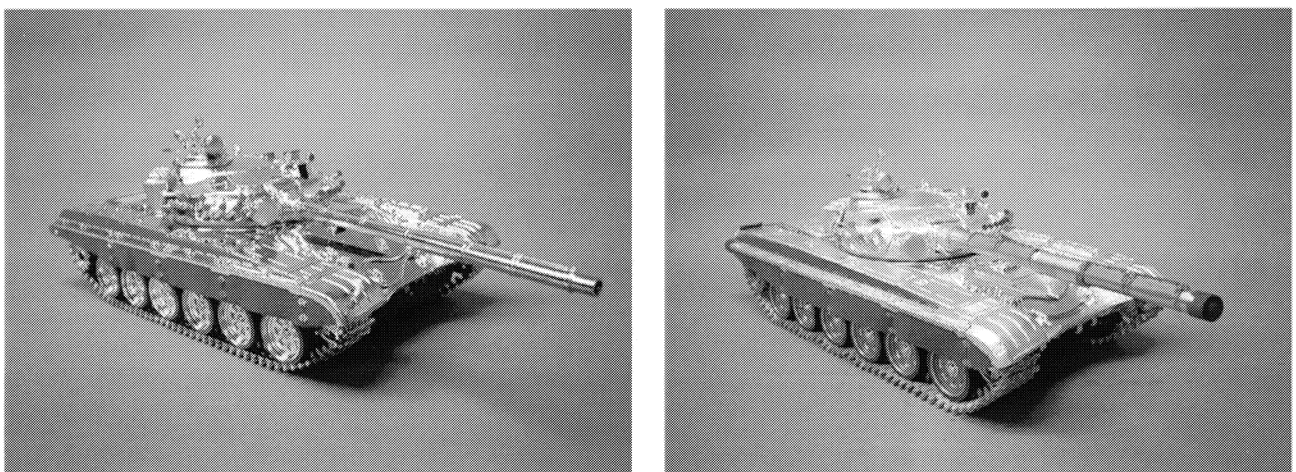

Figure 7. Photographs of $1/35^{th}$ scale model (left) and $1/16^{th}$ scale model (right) of a T72 tank.

Figures 8 and 9 show the results of this Az/El imaging on the $1/35^{th}$ scale models of the SCUD missile launcher and the T72 tank, respectively. These data sets were collected and plotted in Vertical-transmit/ Vertical-receive (VV). Each figure shows sample X-band images at various angles throughout the entire data set. Also shown in these figures are photographs of the targets at angles representative of the angles at which they were measured. The 3.66" cross-range resolution used to generate these images reveals a wide variety of interesting scattering features for both targets. In the T72 data set the individual wheels and tank treads can be distinguished as well as many other features such as the machine gun mount on the turret. Additionally, there are relatively large angular extents (~30deg) where there seems to be a persistent return from the region where the turret meets the body of the tank. Similar features have been seen previously using the other ERADS compact ranges.

The SCUD missile launcher data set shown in Figure 8 also reveals many interesting features. The electromagnetic return from the tires are readily seen at almost all angles except for close to 0 degrees and 180 degrees. The stabilizer arm that holds the missile down toward the forward part of the vehicle can also be observed over a wide variety of angles. In previous papers[5] we have been highly successful in identifying scattering centers by mathematically overlaying Az/El images similar to those seen here with individual photographs that are automatically taken by computer at the angles the images were formed.

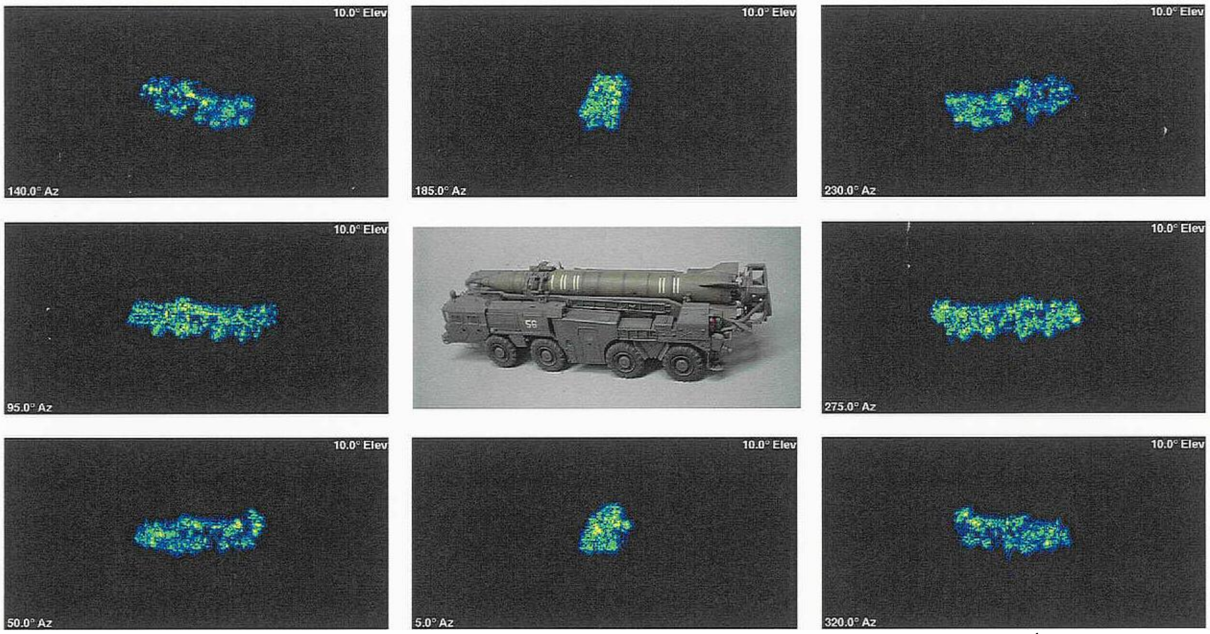

Figure 8. Azimuth vs. Elevation VV cross-range imagery of the SCUD missile launcher using the 1/35th scale model.

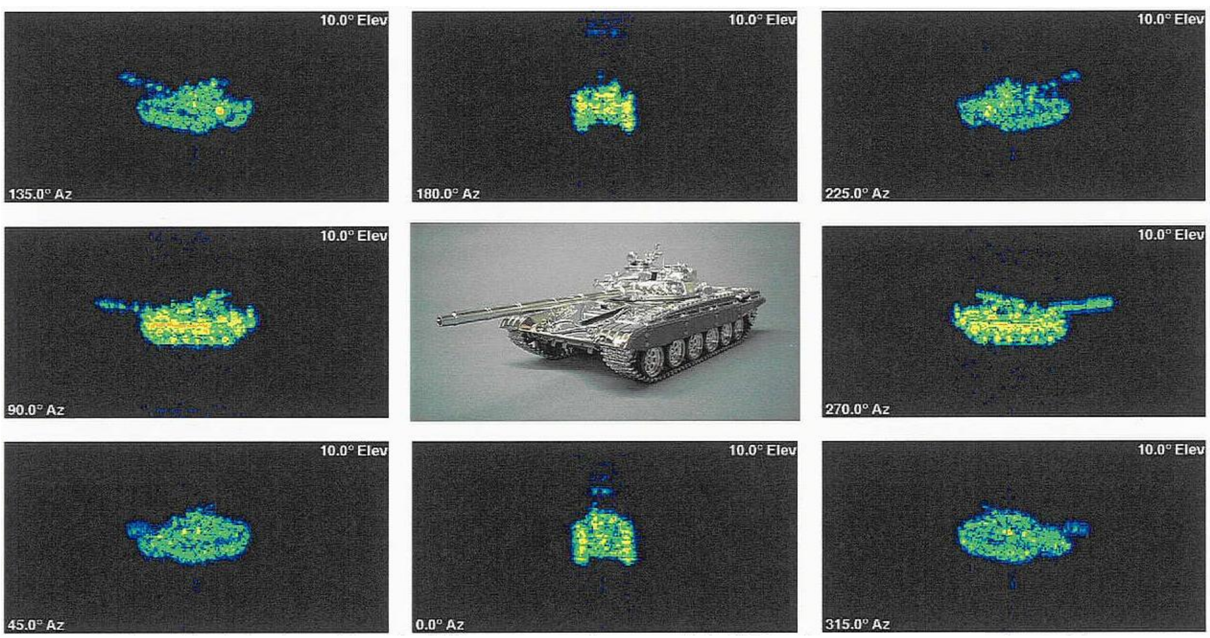

Figure 9. Azimuth vs. Elevation VV cross-range imagery of the T72 tank using the 1/35th scale model.

4. SUMMARY

A new 350GHz compact range has been developed for modeling X-band radar systems using 1/35th scale models. Construction of the compact range is nearly complete, with diagnostic measurements currently being performed. The compact range has a wide bandwidth that allows for better than 6" range resolution. Tests with simple calibration objects have been shown to be in excellent agreement with predictions using computer codes based on the Geometric Theory of Diffraction. Several sample data sets have been collected to produce X-band images of tactical targets. A 20" two-way beam diameter has been measured, corresponding to a target length of 58' full scale within the half power points. ISAR image analysis and comparison of field vs. scale model data will be undertaken to determine the accuracy of using 1/35th scale models.

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